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Session 6 - Tuesday, October 26, 1999
Fuel Burnup Credit
R. Lee (NRC), S. Turner (Holtec Int'l.), Co-Chairs

Session 7 - Wednesday, October 27, 1999
Fission Product Source Terms and Applications
C. Tinkler (NRC), K. Cozens (NEI), Co-Chairs

Spent Fuel Burnup Credit in Casks: An NRC Perspective

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Abstract

Until now, the Nuclear Regulatory Commission's (NRC) approval of criticality safety evaluations for spent fuel in transport and storage casks has been based on analyzing the fuel as though it were fresh and without burnable poisons. The well-known nuclide composition of fresh fuel has provided a straightforward and bounding approach for showing that spent fuel systems will remain subcritical under normal and accident conditions. Burnup credit refers to the approval of criticality safety evaluations that consider the decrease in fuel reactivity caused by irradiation in the reactor. Extensive investigations have been performed in the U.S. and other countries to understand and document the technical issues related to burnup credit. This paper reviews the background for NRC's efforts toward applying burnup credit in the licensing of casks for spent fuel from pressurized water reactors, discusses technical issues affecting the evolving NRC guidance in this area, and outlines the information and efforts needed to further expand such applications of burnup credit.

Introduction

When fuel is irradiated in a reactor, the reactivity of the fuel changes. The variation of fuel reactivity with irradiation is governed by the fuel's changing composition of fissile actinides, non-fissile actinides, fission products, and internal burnable poisons. Ignoring the initial presence of burnable poisons, which may be regarded as fully depleted in spent fuel, the remaining composition changes will cause the net reactivity of the fuel to decrease. Until now, the U.S. Nuclear Regulatory Commission's (NRC) approval of the criticality safety evaluations for commercial spent fuel in casks, including storage, transport, and dual-purpose casks, has been based on analyzing the spent fuel as though it were unirradiated and without burnable poisons. This "fresh-fuel" assumption has provided a straightforward and bounding approach for showing that spent fuel packages will remain subcritical under normal and accident conditions. The extreme conservatism of the fresh-fuel assumption, however, can lead to excessive design requirements for neutron absorbers and/or spacing of the spent fuel.

The term burnup credit refers to allowing the criticality safety of spent fuel systems to be evaluated using analysis approaches that consider the reduced reactivity of irradiated fuel. Actinide-only methods of burnup credit analyze only the effects of actinides on fuel reactivity. In commercial power-reactor fuels that have achieved most of their intended burnup, actinide effects generally account for well over half of the change in reactivity relative to the fresh-fuel assumption, with fission products accounting for the remainder. In the U.S., interest in burnup credit for spent fuel casks has focused mainly on fuel from pressurized water reactors (PWRs) rather than from boiling water reactors (BWRs). This is largely because the smaller pin-array size and correspondingly lower reactivity of individual BWR assemblies, in relation to PWR assemblies, leads to relatively small economic penalties in cask design and capacity when analyzed under the fresh-fuel assumption. Another factor is that the neutronically more complex and variable operation of BWR fuels tends to substantially limit their analysis for burnup credit. This paper reviews the background for NRC's efforts toward applying burnup credit to PWR spent fuel in casks, discusses technical issues affecting the evolving NRC guidance in this area, and outlines the information and efforts needed to further expand such applications of burnup credit.

Background

Other NRC Uses of Burnup Credit in Spent Fuel Storage

The Office of Nuclear Reactor Regulation (NRR) has long allowed the use of burnup credit in the borated spent-fuel storage pools at PWR plants.[1] This is based in part on the established ability of licensees to predict the core burnup behavior over hundreds of reactor years of operation. Additional safety assurance is based on application of the double contingency principle as defined in ANSI/ANS-8.1-1983,[2] and in Title 10, Code of Federal Regulations (10 CFR), Section 72.124(a),[3] which requires two unlikely, independent, concurrent events to produce a criticality accident. For example, if soluble boron is normally present in the spent fuel pool water, the loss of soluble boron is considered as one accident condition and a second concurrent accident need not be assumed. Alternatively, credit for the presence of soluble boron in PWR pools may be assumed in evaluating other accident conditions such as the misloading of fresh fuel assemblies into racks restricted to irradiated fuel. Typically, there is sufficient soluble boron in PWR pools to maintain at least a 5% subcriticality margin even if an entire burnup-dependent storage rack were misloaded with fresh fuel assemblies.

As noted by DOE and others, burnup credit calculations can also be found in the applicants' safety analysis reports (SARs) for two NRC-approved single-purpose dry storage casks for PWR spent fuel. In those cases, the applicants performed burnup credit calculations in evaluating hypothetical underboration events during wet loading or unloading of the dry storage casks. However, the NRC staff's safety evaluation reports for those cases used the fresh-fuel analysis assumption in combination with credit for boron in the water. Boron credit was made possible by creating in the license or certificate a Technical Specification requiring two independent verification controls to ensure sufficient soluble boron concentration during wet loading and unloading operations. This satisfied the double-contingency criterion of 10 CFR 72.124(a) while obviating consideration of loss-of-boron events in the review under 10 CFR Part 72.

Consideration of burnup credit after drying and closure of casks is not necessary in 10 CFR Part 72 storage applications because it has been shown that the probability of fresh-water ingress into sealed dry storage casks is sufficiently low. Specifically, the double-contingency criterion is satisfied by showing that water ingress into a storage cask would require both a flooding event and a severe accident that would cause gross seal failure. On the other hand, transportation regulations under 10 CFR Part 71 include explicit requirements for assuming fresh-water inleakage in the criticality analysis of packages used for transporting fissile materials.[4] Sections 6.5.4 and 6.5.5 in NUREG-1617, "Standard Review Plan for

Transportation Packages for Spent Nuclear Fuel," further discuss the water-inleakage considerations for spent-fuel evaluations under 10 CFR Part 71.[5]

Burnup Credit in Other Countries

Several regulatory bodies outside the U.S. have allowed various uses of burnup credit in wet storage and handling operations, and also in reprocessing. However, transportation uses of burnup credit have been granted to-date only in France. The French reprocessing program has developed an extensive set of proprietary validation data to support the limited credit needed for shipping modern PWR fuels with higher initial enrichments in the existing fleet of casks. Safety authorities in several other countries, including the United Kingdom and Japan, are now working toward similar uses of burnup credit in transport packages. The NRC research program is now evaluating options for acquiring validation benchmarks from French and other foreign or proprietary sources as needed to support expansion of the scope and level of NRC-approved burnup credit in casks. As an indicator of the high level of interest in this field, it is noteworthy that this year's International Conference on Nuclear Criticality Safety featured four technical sessions with nineteen papers devoted to the uses of burnup credit.[6]

NRC Guidance on Burnup Credit Methods for PWR Spent Fuel in Casks

The U.S. Department of Energy (DOE) has worked on the development of a topical report that proposes a method for incorporating actinide-only burnup effects in the analysis of casks for transporting and storing spent fuel from PWRs.[7] The topical report has gone through two cycles of revisions in response to NRC's review and comments, yet outstanding technical issues and uncertainties have prevented NRC from granting the requested approval. Nevertheless, based in part on the technical information provided in the DOE topical report, and supplemented by information available from other sources, the NRC Spent Fuel Project Office (SFPO) issued in May 1999 the initial version of its interim staff guidance document, ISG-8 Revision 0.[8] That initial guidance recommended approving the DOE methodology for use only when the spent fuel is modeled at 50% of the verified and adjusted burnup level from plant records. This 50% limit on the assumed burnup served to cover the staff's remaining issues and uncertainties concerning the proposed methodology. On May 17, 1999, the NRC staff held a public workshop[9] to introduce ISG-8 and discuss NRC and industry perspectives on the further development of burnup credit for PWR spent fuel in casks.

To support the staff's phased efforts in this area, the NRC initiated a research program on burnup credit in early 1999. That research program is the topic of another paper to be presented at this meeting.[10] The initial phases of the research program have included an analysis effort focused on supporting the early revision of ISG-8 to allow greater levels burnup credit. On July 30, 1999, the first results from that effort enabled SFPO's issuance of Revision 1 of ISG-8.[11] This completely rewritten version of the NRC guidance recommends a basis for cask-specific approval of PWR actinide-only burnup credit analyzed at essentially 100% of ar .ssembly's verified and adjusted burnup level from plant records. One of the main limitations o: the guidance is that its direct application is restricted to PWR fuels that have not used burnable absorbers. It is worth noting that the same restriction is found in the method proposed by DOE. A copy of Revision 1 of ISG-8 is included herein as Appendix A. Comments on related modeling and validation issues that affect the further evolution of ISG-8 are included in bulleted form in Appendix B.

Technical Considerations for Revision 1 of ISG-8

This section briefly discusses the technical considerations for selected aspects of Revision 1 of ISG-8. In particular, these comments pertain to Items 1 and 6 of the ISG-8 recommendations.

Item 1 in the Recommendations Section of ISG-8 Rev.1 allows the use of a so-called loading offset for spent fuels with initial ^{235}U enrichments between 4 and 5%. The offset effectively reduces the burnup assumed in calculating the actinide inventories in the affected fuels. The need for this offset arises from the lack of isotopic assay data from spent fuels in the 4 to 5% enrichment range. This offset is an example of how conservative modeling adjustments can be judiciously used to compensate for validation uncertainties that arise from modest extrapolations beyond the measured data.

In establishing the adequacy of the loading offset approach within the current context, the staff has noted the following: All other factors being equal, an increase in initial enrichment lowers the contribution from actinides to the reduced reactivity of spent fuel, thereby increasing the relative contribution from fission products. Thus, the neglect of fission products in actinide-only burnup credit is especially helpful in further offsetting the uncertainties from this limited extrapolation to higher initial enrichments. Such would not be the case if one were to consider an extrapolation to higher burnups. This is because the actinide contribution to reducing the reactivity of irradiated fuel increases much more rapidly with burnup than does the contribution from fission products.

Item 6 in the Recommendations Section of ISG-8 calls for the applicant to provide design-specific analyses that estimate the additional reactivity margins available from fission product and actinide nuclides not included in the licensing safety basis. As discussed below, this recommendation arises from the staff's efforts at addressing the following question: Can the combined effects of uncertainties and approximations in actinide-only burnup credit outweigh the margins from the neglect of fission products and ^{236}U?

At three points in DOE's topical report (Sections 3.2, 4.1.5, and 4.2.3.3), a portion of the large reactivity margins arising from the method's neglect of fission products and ^{236}U is used in attempting to bring closure to an issue. In response to requests from the NRC staff, the current Revision 2 of the topical report now includes in Table 7-4 a tally of the uses of estimated fission-product (and ^{236}U) reactivity margins. Specifically, for initial enrichments of 3.0, 3.6, and 4.5 wt% ^{235}U and burnups of 15, 30, and 45 GWD/MTU, the table subtracts from the estimated fission-product margins three reactivity allowances to account for (a) the unmodeled higher reactivity of fuel assemblies in which control rods were inserted during part of the burnup and (b) uncertainties associated with criticality validation and computer code adequacy issues. The report's tabulated results show a residual margin of at least 2.1% Δk_{eff} in all cases. The topical report and its references, however, fail to provide necessary information about the assumptions and models used in estimating the fission-product and ^{236}U margins and in establishing allowances for the higher reactivity of fuels burned with control rods inserted.

The staff's initial confirmatory analyses, performed with assistance from the NRC research program, have been focused on understanding the estimation and uses of the fission-product and ^{236}U reactivity margin. The NRC's calculations on different cask models have demonstrated that the estimated fission-product and ^{236}U margins vary substantially between cask designs. For example, higher poison loadings in the basket reduce the margins by capturing neutrons otherwise absorbed by fission products. Some of the cask models analyzed by the NRC have yielded calculated fission-product and ^{236}U margins significantly smaller than those in DOE's topical report. As shown by example in Table 1, subtracting the topical report's three reactivity allowances from the NRC-calculated margins for fission products and ^{236}U was found to leave negative residual margins at certain values of low initial enrichment and low burnup. This result can be explained in part by noting that DOE's assumed reactivity allowances for the reactivity effects of burnup in the presence of control rods are greatest at low initial enrichments and constant beyond burnups of 15 GWD/MTU. It is possible, however, that such combinations of low burnup and low initial enrichment would fall below the burnup credit loading curve for the respective cask design.

In response to NRC questions, section 7.4 of the DOE topical report (i.e., Rev.2) discussed several smaller margins, in addition to those from neglecting fission products and ^{236}U, that are associated with apparent modeling conservatisms in the report's actinide-only methodology for burnup credit. Such additional margins would generally tend to offset some or all of the negative residual margins that might appear in cask-specific versions of DOE's Table 7-4. However, as noted in the topical report, the magnitudes of the individual margins are relatively small, variable, and poorly quantifiable. More importantly, most of the additional margins are based on comparisons against the typical or mean case and therefore do not cover the full range of possible or credible fuel loadings that would be allowed under the report's burnup credit method. The NRC staff therefore concludes that it is not possible, based on information considered to-date, to ensure categorically that the aggregate of such additional margins is large enough to offset actinide-only uncertainties in casks where the margins from the neglect of fission products are especially small. The staff expects that further insights into the existence and magnitude of residual margins will emerge from the applicants' cask-specific estimates of (1) the margins from neglected fission product and actinide nuclides and (2) the reactivity effects of uncertainties and potential nonconservatisms in the actinide-only methods.

What Next?

Comments received to-date have indicated an interest in extending burnup credit methods to include PWR fuels that have used burnable or removable absorbers. For work to proceed in this area, the NRC staff and the burnup-credit applicants will need information on the past and present uses of burnable or removable absorbers in PWR fuel designs.

From the preceding discussion on estimation of additional margins, it also appears that a better understanding is needed of reactivity effects in PWR fuels in which control rods were inserted during a significant portion of the burnup history. In particular, a better assessment of the scope and magnitude of rodded burnup histories in the worst-case operating cycles at worst-case PWR plants is needed to support the NRC staff's evaluation of approaches to higher levels of burnup credit.

Therefore, the NRC staff is requesting assistance from the industry in compiling the following types of information:

1. Past and present uses of removable and burnable internal poisons in PWR fuel designs:

(a) What poison materials (e.g., Gd, B, Er) have been used, in what amounts (e.g., in grams of poison per cm^3, or per cm of fuel pin, or per cm of fuel assembly), in what form (i.e., mixed with UO_2, coated on fuel pellets, in poison-only rods, etc.), and in what geometry (i.e., representative pin-by-pin poison zonings)?

(b) Information from the preceding item collated, as warranted, over ranges of (i) initial U-235 enrichment, (ii) design or actual burnup, and (iii) assembly design geometry (i.e., grouped by fuel vendor and pin array size - B&W15x15, W17x17, CE14x14, etc.).

(c) For movable or removable poisons, the typical or bounding histories of poison use in an assembly (e.g., 15 GWD/MTU, first-cycle-only, part-length axial location and extent, etc.)

2. Past and present uses of control rods for load following and power shaping in U.S. PWRs:

   The NRC staff is aware that at-power insertion of control rods for load following has not been extensively practiced in the U.S. However, because the NRC licenses cask designs to take spent fuel from many or all plants, it is important to know about the worst-case rodded burnup histories at the worst-case plants. Of interest would be an identification of the worst-case plants and cycles and, for those plants and cycles, information on what kinds of control rods were used, how deep, how long (i.e., in terms of burnup), in which burnup cycles (e.g., first only) and in how many and which kinds of assemblies.

All other things being equal, spent fuel burned in the presence of thermal neutron poisons can have a significantly higher k_{eff} than fuel burned without poisons. This is because the poisons harden the energy spectrum of neutrons absorbed by fuel, leading to more breeding of fissile Pu. While the poisons may fully deplete with burnup, the more reactive actinide compositions remain significantly intact. In considering burnup credit, the NRC and its applicants will need to determine which categories of internal poison designs bound others with respect to the computed in-package k_{eff} of spent fuel.

The higher reactivity of spent fuel burned in the presence of poisons is a strong function of initial enrichment; namely, lower-enriched fuels show a much stronger reactivity effect for a given burnup and poison loading. This is because lower-enriched fuel has less initial ^{235}U to deplete, yet breeds fissile Pu faster, per unit of burnup, than higher-enriched fuel. Therefore, the bounding poison categories may have to be evaluated over two or more ranges of initial ^{235}U enrichment and final assembly-average burnup (see item 1(b) above).

The requested information on internal poisons should be comprehensive - representing essentially all fuel cycles and assemblies at all U.S. PWRs - to enable consideration of significant burnup credit for all such fuels. To the extent that detailed information on fuel designs may be proprietary, appropriate measures will be taken to either protect the proprietary interests or else convert the information to a less-detailed, nonproprietary form that still meets the needs of NRC and its applicants.

The information on worst-case rodded burnup histories is especially relevant when considering the fact that any fission chain reactions in spent fuel happen at the less-burned top ends of the fuel assemblies. It appears that worst-case axial burnup profiles may be closely correlated with rodded burnup histories. If that is true, we must account not only for the lower burnup at the top of the fuel, but also the more reactive actinide compositions associated with part of that burnup having occurred in the presence of control rods.

The level and scope of appropriate burnup credit is proportional to the information available. The current Revision 1 of ISG-8 does not include burnup credit for PWR fuels burned with internal poisons and does not address fission product credit. The NRC staff would like to lessen those restrictions, but needs the kinds of information described above in order to proceed.

References:

1. Laurence Kopp, "Guidance on the Regulatory Requirements for Criticality Analysis of Fuel Storage at Light-Water Reactor Power Plants," NRC Memorandum to Timothy Collins, U.S. Nuclear Regulatory Commission, August 19, 1998.
2. American Nuclear Society, October 1983, "Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors," ANSI/ANS-8.1-1983, La Grange Park, IL.
3. Code of Federal Regulations, Title 10, Part 72, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel and High Level Waste," January 1999.
4. Code of Federal Regulations, Title 10, Part 71, "Packaging and Transportation of Radioactive Material," January 1999.
5. NUREG-1617, "Standard Review Plan for Transportation Packages for Spent Nuclear Fuel," U.S. Nuclear Regulatory Commission, March 1998.
6. Sixth International Conference on Nuclear Criticality Safety, Versailles, France, September 20-24, 1999.
7. "Topical Report on Actinide-Only Burnup Credit for PWR Spent Fuel Packages," DOE/RW-0472, Rev. 2, U.S. Department of Energy, September 1998.
8. Spent Fuel Project Office Interim Staff Guidance - 8, Revision 0, U.S. Nuclear Regulatory Commission, May 16, 1999.
9. Chester Poslusny, "Summary of Public Workshop with the Nuclear Energy Institute on Burnup Credit," NRC Memorandum to Susan Shankman, U.S. Nuclear Regulatory Commission, May 27, 1999. (Meeting held on May 17, 1999)
10. Cecil Parks, Charles Nilsen, "NRC Research Program on Burnup Credit," 27th Water Reactor Safety Information Meeting, Bethesda, MD, October 25-27, 1999.
11. Spent Fuel Project Office Interim Staff Guidance - 8, Revision 1, U.S. Nuclear Regulatory Commission, July 30, 1999. (http://www.nrc.gov/OPA/reports/isg8r1.htm)

Table 1. Results from NRC Confirmatory Analysis of Table 7-4 in DOE Topical Report, DOE/RW-0472 Rev.2, Tally of the Use of Fission-Product and ^{236}U Margin for Addressing Uncertainties of Actinide-Only Burnup Credit

Enrichment (wt% ^{235}U) and Burnup (GWD/MTU)		EFPM = Estimated Fission Product and ^{236}U Margin (%Δk_{eff})		DOE's Reactivity Allowances for Uncertainty Issues and Approximations in Actinide-Only Burnup Credit (%Δk_{eff})			Estimated Remaining Margin (%Δk_{eff}) with EFPM from:	
		DOE TR Rev.2	NRC Case A	Criticality Validation Issues	Effect if Control Rods were Inserted During Depletion	Computer Code Adequacy Issues	DOE TR Rev.2	NRC Case A
3.0	15	8.4	4.4	2.0	3.3	1.0	2.1	**-1.9**
	30	13.0	5.9	2.0	3.3	1.0	6.7	**-0.4**
	45	16.0	6.9	2.0	3.3	1.0	9.7	0.6
3.6	15	8.2	4.3	2.0	2.1	1.0	3.1	**-0.8**
	30	12.8	5.6	2.0	2.1	1.0	7.7	0.5
	45	16.2	6.7	2.0	2.1	1.0	11.1	1.6
4.5	15	7.9	4.2	2.0	1.0	1.0	3.9	0.2
	30	12.4	5.6	2.0	1.0	1.0	8.4	1.6
	45	16.1	6.5	2.0	1.0	1.0	12.1	2.5

Appendix A

NRC Spent Fuel Project Office
Interim Staff Guidance - 8
Revision 1
(July 30, 1999)

ISG-8, Rev. 1 - Limited Burnup Credit

Dry Cask Storage | News and Information | NRC Home Page | E-mail

Spent Fuel Project Office

Interim Staff Guidance - 8

Revision 1

Issue: Burnup Credit in the Criticality Safety Analyses of PWR Spent Fuel in Transport and Storage Casks

Introduction:

Unirradiated reactor fuel has a well-specified nuclide composition that provides a straightforward and bounding approach to the criticality safety analysis of transport and storage casks. As the fuel is irradiated in the reactor, the nuclide composition changes and, ignoring the presence of burnable poisons, this composition change will cause the reactivity of the fuel to decrease. Allowance in the criticality safety analysis for the decrease in fuel reactivity resulting from irradiation is typically termed burnup credit. Extensive investigations have been performed both within the United States and by other countries in an effort to understand and document the technical issues related to burnup credit. Much of this work has been considered in the development of the U.S. Department of Energy's Topical Report (TR) on Actinide-Only Burnup Credit for Pressurized Water Reactor (PWR) Spent Nuclear Fuel Packages (DOE/RW-0472).

The technical information provided in the literature and in the various TR revisions, together with the initial confirmatory analyses by the U.S. Nuclear Regulatory Commission (NRC) research program, have provided a sufficient basis for the staff to proceed with acceptance of a burnup credit approach in the criticality safety analysis of PWR spent fuel casks as discussed in the Recommendations below. Although insights gained from reviewing the TR submittals form a part of the basis for the staff's position, this interim staff guidance does not approve the TR or its supporting documentation. The following recommendations provide a cask-specific basis for granting burnup credit, based on actinide composition. The NRC's staff will issue additional guidance and/or recommendations as information is obtained from its research program on burnup credit and as experience is gained through future licensing activities. Except as specified in the following recommendations, the application of burnup credit does not alter the current guidance and recommendations provided by the NRC staff for criticality safety analysis of transport and storage casks.

Recommendations:

1. **Limits for the Licensing Basis.** The licensing-basis analysis performed to demonstrate criticality safety should limit the amount of burnup credit to that available from actinide compositions associated with PWR irradiation of UO_2 fuel to an assembly-average burnup value of 40 GWd/MTU or less. This licensing-basis analysis should assume an out-of-reactor cooling time of five years and should be restricted to intact assemblies that have not used burnable absorbers. The initial enrichment of the fuel assumed for the licensing-basis analysis should be no more than 4.0 wt% ^{235}U unless a loading offset is applied. The loading offset is defined as the minimum amount by which the assigned burnup loading value (see Recommendation 5) must exceed the burnup value used in the licensing safety basis analysis. The loading offset should be at least 1 GWd/MTU for every 0.1 wt% increase in initial enrichment above 4.0 wt%. In any case, the initial enrichment shall not exceed 5.0 wt%. For example, if the applicant performs a safety analysis that demonstrates an appropriate subcritical margin for 4.5 wt% fuel burned to the limit of 40 GWd/MTU, then the loading curve (see Recommendation 4) should be developed to ensure that the assigned burnup loading value is at least 45 GWd/MTU (i.e., a 5 GWd/MTU loading offset resulting from the 0.5 wt% excess enrichment over 4.0 wt%). Applicants requesting use of actinide compositions associated with fuel assemblies, burnup values, or cooling times outside these specifications, or applicants requesting a relaxation of the loading offset for initial enrichments between 4.0 and 5.0 wt%, should provide the measurement data and/or justify extrapolation techniques necessary to adequately extend the isotopic validation and quantify or bound the bias and uncertainty.

Code Validation. The applicant should ensure that the analysis methodologies used for predicting the actinide compositions and determining the neutron multiplication factor (k-effective) are properly validated. Bias and uncertainties associated with predicting the actinide compositions should be determined from benchmarks of applicable fuel assay measurements. Bias and uncertainties associated with the calculation of k-effective should be derived from benchmark experiments that represent important features of the cask design and spent fuel contents. The particular set of nuclides used to determine the k-effective value should be limited to that established in the validation process. The bias and uncertainties should be applied in a way that ensures conservatism in the licensing safety analysis. Particular consideration should be given to bias uncertainties arising from the lack of critical experiments that are highly prototypical of spent fuel in a cask.

Licensing-Basis Model Assumptions. The applicant should ensure that the actinide compositions used in analyzing the licensing safety basis (as described in Recommendation 1) are calculated using fuel design and in-reactor operating parameters selected to provide conservative estimates of the k-effective value under cask conditions. The calculation of the k-effective value should be performed using cask models, appropriate analysis assumptions, and code inputs that allow adequate representation of the physics. Of particular concern should be the need to account for the axial and horizontal variation of the burnup within a spent fuel assembly (e.g., the assumed axial burnup profiles), the need to consider the more reactive actinide compositions of fuels burned with fixed absorbers or with control rods fully or partly inserted, and the need for a k-effective model that accurately accounts for local reactivity effects at the less-burned axial ends of the fuel region.

Loading Curve. The applicant should prepare one or more loading curves that plot, as a function of initial enrichment, the assigned burnup loading value above which fuel assemblies may be loaded in the cask. Loading curves should be established based on a 5-year cooling time and only fuel cooled at least five years should be loaded in a cask approved for burnup credit.

Assigned Burnup Loading Value. The applicant should describe administrative procedures that should be used by licensees to ensure that the cask will be loaded with fuel that is within the specifications of the approved contents. The administrative procedures should include an assembly measurement that confirms the reactor record assembly burnup. The measurement technique may be calibrated to the reactor records for a representative set of assemblies. For an assembly reactor burnup record to be confirmed, the measurement should provide agreement within a 95 percent confidence interval based on the measurement uncertainty. The assembly burnup value to be used for loading acceptance (termed the assigned burnup loading value) should be the confirmed reactor record value as adjusted by reducing the record value by the combined uncertainties in the records and the measurement.

Estimate of Additional Reactivity Margin. The applicant should provide design-specific analyses that estimate the additional reactivity margins available from fission product and actinide nuclides not included in the licensing safety basis (as described in Recommendation 1). The analysis methods used for determining these estimated reactivity margins should be verified using available experimental data (e.g., isotopic assay data) and computational benchmarks that demonstrate the performance of the applicant's methods in comparison with independent methods and analyses. The Organization for Economic Cooperation and Development Nuclear Energy Agency's Working Group on Burnup Credit provides a source of computational benchmarks that may be considered. The design-specific margins should be evaluated over the full range of initial enrichments and burnups on the burnup credit loading curve(s). The resulting estimated margins should then be assessed against estimates of: (a) any uncertainties not directly evaluated in the modeling or validation processes for actinide-only burnup credit (e.g., k-effective validation uncertainties caused by a lack of critical experiment benchmarks with either actinide compositions that match those in spent fuel or material geometries that represent the most reactive ends of spent fuel in casks); and (b) any potential nonconservatisms in the models for calculating the licensing-basis actinide inventories (e.g., any outlier assemblies with higher-than-modeled reactivity caused by the use of control rod insertion during burnup).

Approved

(Original Signed by)

E. William Brach

Appendix B

Presentation Handout

Spent Fuel Burnup Credit in Casks: An NRC Perspective

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1

What is Burnup Credit?

- **Fresh Fuel Assumption:**
  - Analyzing spent fuel as though it were fresh and without burnable poisons leads to excessive requirements for neutron poisons and/or spacing of spent fuel.
- **Spent Fuel Burnup Credit:**
  - Considers the reduced reactivity of irradiated fuel as governed by the changing composition of:
    - **Fissile Actinides** (U-235, Pu-239, Pu-241,...)
    - **Non-Fissile Actinides** (U-238, Pu-240, Am-241,...)
    - **Fission Products** (Rh-103, Cs-133, Nd-143,...)
    - **Fixed Burnable Poisons** (Gd, B, Er,...)

2

International Interest in Burnup Credit

- ICNC'99 had <u>four</u> technical sessions devoted to Burnup Credit
- Existing or Planned Uses of Burnup Credit
  - Storage Pools - PWR and BWR
  - Transport & Storage Casks - PWR only
  - Geologic Disposal - PWR and BWR
  - Reprocessing Plants - PWR and BWR

3

U.S. Efforts on Burnup Credit in Casks (1)

- DOE Work: Topical Report on Proposed Method for Actinide-Only Burnup Credit in PWR SNF Casks
  - Topical Report went through two cycles of revisions based on NRC's review and comments.
  - NRC has not approved DOE Topical Report due to outstanding technical issues and uncertainties.

4

U.S. Efforts on Burnup Credit in Casks (2)

- NRC Work: Interim Staff Guidance on Burnup Credit in PWR Spent Fuel Casks
  - March 1999: Started NRC Research Program on Burnup Credit.
  - May 1999, <u>ISG-8 Rev.0</u>: Approval of Limited Actinide-Only Burnup Credit based on 50% of Verified Burnup. NRC/NEI Workshop.
  - July 1999, <u>ISG-8 Rev.1</u>: Approval of Limited Actinide-Only Burnup Credit based on 100% of Verified Burnup. Applications expected in early 2000.
- NRC expects to issue further guidance revisions to reflect new research and licensing experience.

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Proposed Form of Burnup Credit in Casks

- Input three pieces of fuel information:
  - Fuel Assembly Design:
    - Dimensions, Initial enrichment, Internal poisons
  - Assembly-Average Burnup
  - Minimum Cooling Time
- Output a cask loading criteria curve:
  - Minimum Burnup versus Initial Enrichment

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Details of Fuel Power History Affect the Reactivity of Spent Fuel

- Parameters for PWR Fuel Power History:
  - Absorber Rods, Dissolved Boron, Moderator Temperature
  - Fuel Temperature, Specific Power
- Assemblies of given Design, Average Burnup, and Cooling Time have a wide range of:
  - Isotopic Compositions
  - Burnup Profiles - Axial, Horizontal

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Proposed Analysis Approach for Burnup Credit in Spent Fuel Casks

- For Assemblies of given Design, Average Burnup, and Cooling Time:
  - Determine burnup isotopic compositions and profiles that maximize the computed in-cask reactivity.
  - Calculate k_{eff} for a payload of such assemblies under normal and accident conditions in the cask.
- Use k_{eff} results over a range of burnups and initial enrichments to develop a Burnup Credit Loading Curve.

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Burnup Credit Modeling and Validation Color Code

- Green - Adequate for use with full burnup credit
- Yellow - Adequate for Limited Actinide-Only Burnup Credit (ISG-8 Rev.1)
- Red - Potential basis for expanded or full burnup credit

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Modeling Issues for Burnup Credit (1)

- **Fuel Isotopics: Burnup History Parameters**

Actinide-only k_{eff} is bounded by maximizing:
- Solid Poisons (Control rods, Internal poisons, etc.) [Red]
- Dissolved Boron [Yellow]
- Moderator Temperature [Yellow]
- Fuel Temperature [Yellow]
- Specific Power [Yellow]

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Modeling Issues for Burnup Credit (2)

- **In-Cask Neutronics: Horizontal Burnup Profiles within Assemblies**
  - Effects of tilted ! .nup profiles within assemblies are especially significant in small casks.
  - Most-reactive credible configuration must consider relative orientations of assemblies with strong burnup tilts.
  - DOE has proposed an acceptable method for modeling the effects of horizontal burnup profiles. [Green]

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Modeling Issues for Burnup Credit (3)

- **In-Cask Neutronics: Axial Burnup Profiles and End Effects**
  - Ends of spent fuel are less burned, more reactive.
  - Fission chain reaction is localized at least burned end.
  - Determine and assume most reactive burnup profiles.
  - DOE has evaluated axial burnup profiles based on in-core data for >3000 assemblies at several PWRs. [Yellow]
  - NRC working with NEI and OECD/NEA to further evaluate axial profiles, noding, and end-effects modeling for various neutronic conditions in casks. [Red]

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A Simple Validation Question:

- **Fact: We can calculate criticality in PWRs with known accuracy.**
- **Question: Can we somehow conclude from this that we can calculate the k_{eff} of spent fuel in casks with:**
  - (a) Similar accuracy? Answer: No.
  - (b) Some other level of accuracy? Answer: Maybe. But: 1) it's not easy; 2) benefits limited; 3) more data and analysis needed.
- **Why is this so?**
  - Neutrons see irradiated fuel in casks differently from in a reactor
  - Core calculations benefit from feedback. No feedback from spent fuel.
  - What is needed? Let's try to understand this ...

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Validation

- Method Validation = Evaluating and using the method bias and its uncertainty
- We can start to understand the "Simple Validation Question" by comparing PWR and Spent Fuel Cask Criticality in terms of:
  - Phenomena
  - Analysis
  - Methods
  - Validation

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Understanding the Validation Issue (1)

- PWR Cores - Predicting Restart Criticality
  - **Phenomena:** Whole-Core criticality in similar cores with mixed cycle burnups, designed-in power flattening, no end effects.
  - **Analysis:** Predict core criticality knowing past restart data and detailed fuel operating history.
  - **Typical Methods:**
    - Isotopics - 2D Transport, Multigroup
    - Criticality - 2D/3D Transport/Diffusion, Approximate Mesh Geometry, Multigroup/Few-Group
  - **Validation:** Accumulated PWR restart data have taught code developers and users how to predict PWR restart criticality.

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Understanding the Validation Issue (2)

- Cask Burnup Credit - Ensuring Subcriticality
  - **Phenomena:** Localized criticality at fuel ends; Variety of fuel loadings; Variety of cask designs; Unique material geometries for neutron absorption and scattering.
  - **Analysis:** Dead Reckoning - no feedback. Try to bound the maximum k_{eff}. Assume most reactive fuel power histories and burnup profiles.
  - **Typical Methods:**
    - Isotopics - 1D/2D Transport, Multigroup
    - Criticality - 3D Monte Carlo, Exact Geometry, Multigroup or Continuous Energy
  - **Validation:** (see next slides...)

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Potential Sources of Data for Validating Cask Burnup Credit Methods (1)

- **Isotopic Validation:**
  - Radiochemical assay of spent fuel
    - Actinide Data for burnups ≤40 GWD/MTU) [Yellow]
    - Actinide Data for initial enrichments >4% [Red]
    - Actinide Data for burnups >40 GWD/MTU [Red]
    - Actinide Data for fuels with internal absorbers [Red]
    - Fission Product Data [Red]
  - Nondestructive assay of spent fuel
    - Advanced/Novel Methods [Red]

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Potential Sources of Data for Validating Cask Burnup Credit Methods (2)

- **Combined Isotopic and Criticality Validation:**
  - Criticality in Power Reactors [Red]
    - Planned in DOE Topical Report for Disposal Criticality
    - Other approaches
  - Criticality in HEU Reactors [Red]
  - Subcritical Measurements on Spent Fuel [Red]

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Potential Sources of Data for Validating Cask Burnup Credit Methods (3)

- **Criticality (k_{eff}) Validation:**
  - Lab Critical Experiments
    - Existing UO_2 and MOX Data [Yellow]
    - New experiments relevant to spent fuel, end effects, etc. [Red]
  - Reactivity Worth Experiments
    - Existing and Planned Foreign or Proprietary Data (e.g., French, British) [Red]
    - Planned REBUS Experiments (Belgonucleaire) [Red]
    - Other New Experiments (e.g., Proteus, U.S. Ceres) [Red]

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ISG-8 Rev.1: NRC Guidance on Burnup Credit for PWR Spent Fuel in Casks (1)

- Limits for Licensing Basis:
  - Credit from Actinides Only in UO_2 PWR Fuel
  - Maximum credited burnup is 40 GWD/MTU
  - No fuel designs with burnable poisons
  - Assume cooling time of 5 years (minimum)
  - Loading offset for enrichments between 4 and 5%
  - Fuels and actinide compositions outside these limits require extension of the isotopic validation:
    - Provide measurement data, and/or
    - Justify techniques for extrapolating bias and uncertainty

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ISG-8 Rev.1: NRC Guidance on Burnup Credit for PWR Spent Fuel in Casks (2)

- Validation of Codes and Methods:
  - Derive isotopic bias & uncertainty from applicable fuel assay benchmarks.
  - Derive k_{eff} bias & uncertainty from benchmark experiments representing major features of cask and spent fuel.
  - In computing k_{eff}, use only those nuclides established in validation process.
  - Consider the bias uncertainties arising from lack of experiments that are prototypic of spent fuel in the cask.
  - Apply bias and uncertainties only in ways that ensure conservatism in the licensing safety analysis.

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ISG-8 Rev.1: NRC Guidance on Burnup Credit for PWR Spent Fuel in Casks (3)

- Model Assumptions for Licensing Basis:
  - In isotopic calculations, use the fuel design and power history parameters that maximize k_{eff} in the cask.
  - Calculate k_{eff} using models and assumptions that allow adequate representation of important physics, including:
    - The axial and horizontal burnup profiles within assemblies
    - The more reactive actinide compositions of fuels burned with inserted control rods or internal absorbers
    - Local neutron scattering and absorption effects near the least-burned end of the fuel

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ISG-8 Rev.1: NRC Guidance on Burnup Credit for PWR Spent Fuel in Casks (4)

- Cask Loading Curves:
  - As a function of initial enrichment, plot the Assigned Burnup Loading Value above which fuel assemblies may be loaded.
  - Loading curves based on analysis for 5-year cooling.
  - Load only assemblies cooled 5 years or more.

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ISG-8 Rev.1: NRC Guidance on Burnup Credit for PWR Spent Fuel in Casks (5)

- Assigned Burnup Loading Value:
  - Applicant describes administrative procedures by which cask user ensures that fuel loading is within specifications.
  - Procedures include a measurement that confirms the reactor record value of assembly burnup.
    - Measurement may be calibrated to the reactor records for a representative set of assemblies.
    - Confirmation: Measured and record burnup values agree within a 95% confidence interval based on measurement uncertainty.
  - Reduce the confirmed record value of assembly burnup by the combined uncertainties in the records and the measurement.

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ISG-8 Rev.1: NRC Guidance on Burnup Credit for PWR Spent Fuel in Casks (6)

- Estimate of Additional Reactivity Margin:
  - Estimate the additional reactivity margins from actinides and fission products not included in licensing safety basis.
  - Verify the analysis methods for estimating margins using:
    - Available experimental data (e.g., isotopic assays)
    - Computational benchmarks comparing against independent methods and analyses.
  - Assess estimated margins against:
    - Any uncertainties not directly accounted for in the modeling or validation process (e.g., non-prototypicality of k_{eff} benchmarks)
    - Any potential nonconservatisms in the licensing-basis models and assumptions (e.g., neglect of outlier rodded burnup histories)

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PWR Spent Fuel Burnup Credit in Casks: What Next?

- **Near Term Issues:**
  - Burnable Absorbers [Red]
    - Absorber designs in PWR fuels (Gd, B, Er,...)
    - Applicable isotopic validation
    - Burnup computational models -1D and 2D
  - Rodded Burnup Histories [Red]
    - At-power use of control rods in U.S. PWRs
      - **Worst-Case Plants: How, How much, Where, When?**
    - Applicable isotopic validation and modeling
  - Burnup Verification Measurements [Yellow]
  - Fission Product Margin and Uncertainties [Red]

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PWR Spent Fuel Burnup Credit in Casks: Conclusion

- NRC will issue further technical guidance on Burnup Credit as information and insights emerge from:
  - Cooperative Research
  - Licensing Experience
  - Industry Data and Analysis (as available)

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